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The propagation of electron beam currents much greater than the space charge limit and collective ion acceleration in evacuated dielectric guides was investigated. Experiments at Spire and at the Gamble I facility of NRL show that the beam front propagation velocity is not affected by the dielectric guide downstream from the anode region of the accelerator. The propagated current, however, depends strongly on guide parameters, and is considerably diminished in a shortened guide configuration.

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20. Abstract (Concluded)

Collectively accelerated ions were not observed using the 40 ns, 200 keV electron accelerator at Spire, although earlier experiments using longer, lower energy pulses showed considerable ion acceleration. Proton energies more than 14 times the electron beam energy were observed during the experiment on Gamble I. An estimated 2×10^{9} protons at 12 MeV or greater along with 3×10^{11} protons at 5 MeV or greater were observed in a single shot. The origin of the collectively accelerated protons was principally in the anode foil of the accelerator.

Suggestions for increasing the energy and yield of collectively accelerated ions include improving the homogeneity of the downstream plasma and reducing the magnetic field of the propagating electron beam current.

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FOREWORD

I wish to acknowledge important contributions to this project by the following individuals. The program at Spire was greatly aided by discussions and suggestions from A. C. Greenwald and the technical help of P. F. Meroth and S. L. Achorn. The experimental work on the Gamble I facility at the Naval Research Laboratory would not have been possible without the considerable aid of G. Cooperstein, F. C. Young, J. J. Condon and A. T. Robinson of NRL, R. L. Gullickson of the Defense Nuclear Agency and P. G. Halverson of the University of Arizona.

SECTION 1
INTRODUCTION

1.1 GENERAL

The phenomena of electron beam propagation and collective ion acceleration in evacuated dielectric guides were discovered several years ago in experiments at Spire Corporation(1,2) and have been investigated at Spire(3,4,5) and other laboratories(6,7,8) since that time. In these experiments a high-current pulsed electron beam is accelerated through the anode of a field-emission diode into the evacuated dielectric guide. The beam quickly forms a virtual cathode a short distance from the anode, and the following electrons are reflected and spread radially by the electric field of the virtual cathode until they impinge on the wall of the dielectric guide. A low-temperature plasma is formed at the irradiated surface of the guide by various processes, including volume breakdown of the dielectric, surface flashover, and ionization and breakdown of desorbed gas. The ions of this plasma are accelerated electrostatically into the virtual cathode, where they partially neutralize the electronic space charge. The electron beam can now propagate down the guide.

The transported electron current appears to propagate behind a sharply defined "front" region where, in our qualitative model, the beam is not neutralized and impinges on the wall of the guide. The unneutralized beam current far exceeds the space charge limit under these conditions and forms a virtual cathode near the front. The speed of the front has been shown to be independent of the guide material, guide diameter, and ratio of cathode-to-guide diameter for several experimental configurations. The speed of the front shows some correlation, however, with the peak energy of the accelerated electrons. Although individual experiments show little variation of the front velocity with electron energy, a rough energy$^{1/2}$ scaling is indicated over a range from 100 keV to 1.5 MeV.(9,10)

Collectively accelerated ions, prinicipally protons, have been observed in several experiments on propagating electron beams in dielectric guides.(3,4,7,8) Two groups of ions have been registered. The first group apparently has velocities equal to that of the propagating front and energies approximately equal to the energy of the accelerated electron beam. The second group has energies of 3 to 10 times the energy of the electron beam and is only observed under conditions of high injected electron current and rather poor propagation of the electron beam. The origin of the high-energy ions is not understood and is presently under study in several laboratories.

The scaling of the front velocity and the approximate constancy of this velocity with experimental configuration are qualitatively similar to measurements of beam propagation and collective ion acceleration in Luce diodes(11,12,13) and to experiments in which relativistic electron beams are injected into a puff of gas near the anode of the accelerator.(14) Similar results have been reported on experiments in which pulsed electron beams were accelerated into thin plastic foil anodes(15) and nearly constant velocities of the propagating beams were measured. Collectively accelerated ions with energies several times the electron energy were also observed in these experiments.

One-dimensional calculations and computer simulations of the propagation of electron beams indicate that the fronts of relativistic electron beams neutralized near the anode should scale as the velocity of the neutralizing ions, which have an energy of about that of the electron beam. A high-energy tail of the ion velocity distribution has been seen in one-dimensional computer simulations(15) as well as time-dependent phenomena such as high-frequency pulsations.(16) It is likely, however, that the one-dimensional simulations do not adequately represent the complicated phenomena involved in these experiments.

1.2 SPIRE PROGRAM

Spire's earlier program(1-5) demonstrated that a considerable fraction of the electron beam current injected into a dielectric guide could be propagated in an evacuated dielectric guide even though the current greatly exceeds the space charge limiting value. Up to 80 percent of the injected current was propagated over distances of several tens of centimeters. Additionally, it was shown that the energy of the collectively accelerated ions may scale with length of guide and the current density of the injected electron beam.

These results were obtained using a relatively low energy (less than 85 keV), slowing rising current pulse (typically 15 kA in 100 ns FWHM pulse) from the Spire SPI-PULSE 6000 accelerator. The possibility of propagating electron beams over longer distances and the purpose of obtaining higher energy, collectively accelerated ions led us to the program reported here, in which the experimental conditions were considerably different from those investigated by us or in other laboratories.

Two very different electron accelerators were chosen for the experimental program. The first, the SPI-PULSE 600 at Spire, is a new machine which produces a much shorter, higher energy pulse of electrons than used in the earlier experiments. A nearly "square", 40 ns pulse of electrons with an average energy up to 200 keV and currents to 22 kA can be produced by this 9-ohm charged transmission line when operated with an impedance-matched accelerator diode.

The second electron accelerator chosen was Gamble I at the Naval Research Laboratory. This low-impedance, high-energy machine typically produces 500 to 800 keV electron beams with pulse widths of 70 ns and currents greater than 100 kA. This accelerator represents a factor of 10 scale-up in beam energy and current over the original experiments with the SPI-PULSE 6000.

During the past two years we have performed a series of experiments on electron beam propagation and collective ion acceleration in dielectric guides of several materials and geometries over a rather wide range of experimental parameters. Section 2 describes the experiments and results of the investigation of beam propagation. Section 3 summarizes the work on collective ion acceleration; Section 4 is a discussion of the results, a comparison with other collective ion experiments, and a suggested technique to enhance the energy and yield of accelerated ions. Section 5 summarizes the results and conclusions of the research and recommends directions for further investigation.

SECTION 2
ELECTRON BEAM PROPAGATION

2.1 EXPERIMENTS AT SPIRE

The initial efforts of the program were to investigate electron beam propagation in dielectric cylinders and converging cones. Experiments were designed to study the effects of electron beam energy, injected current and current density, and guide geometry on the velocity of propagation of the beam front and the current transmitted through the guide.

2.1.1 Electron Accelerator

All of the experiments at Spire were conducted using the SPI-PULSE 600 electron accelerator, which is a 9-ohm solid-dielectric transmission line, statically charged by a Van de Graaff generator to voltages up to 400 kV. The line is discharged by a spark switch into a field-emission diode, producing an approximately 40-ns pulse with energies up to 200 keV and currents of 22 kA when the diode impedance is matched to the line. Adjustments to the cathode diameter and the anode-cathode spacing produce a variety of beam parameters, from high-energy, low-current beams with overmatched diodes to low-energy, high-current beams when the diode impedance is considerably less than the 9-ohm line impedance.

The field-emission diode of the accelerator is a textured graphite cathode located at the end of the switch assembly and a partially transparent anode mesh at ground potential. The anode is replaceable by meshes of different opacity or by metallic foils. The diode region is evacuated to a pressure in the range of 10^{-4} torr by an oil diffusion pump, which also evacuates the chamber in which the dielectric guides and beam diagnostics are located.

Table 2-1 gives the characteristics of the SPI-PULSE 600 accelerator under typical operating conditions.

2.1.2 Diagnostics

The principal diagnostics used in the beam propagation experiments were a movable Faraday probe and the voltage and current monitors of the electron accelerator. The Faraday probe was inserted inside the dielectric guides to measure the

TABLE 2-1. CHARACTERISTICS OF SPI-PULSE 600 ELECTRON ACCELERATOR

CHARGED LINE

Capacitance	1.9 nF
Impedance	9 ohms
Electrical length	40 ns

ELECTRON BEAM

Charging Potential (kV)	Cathode Diameter (mm)	A-K Gap (mm)	Beam Voltage (kV)	Beam Current (kA)
150	38	3.5	70	7
300	38	3.5	140	16
300	38	7	180	9
300	76	3.5	120	22
400	38	3.5	190	22

arrival time of the beam front and the total transmitted current as a function of axial position in the guide. The probe was a 5.1-cm-diameter aluminum plate grounded through a 0.26-ohm resistor; in some experiments the probe was shielded by a 6-micrometer-thick aluminum foil to suppress signals from electrons and ions of the low-temperature plasma formed at the walls of the guide.

The temporally resolved characteristics of the electron beam were measured by a capacitive voltage monitor and a current shunt mounted on the diode of the electron accelerator. The signals from these diagnostics were displayed for every shot on high-frequency Tektronix 519 oscilloscopes. Figure 2-1 is a schematic diagram of the diode region of the accelerator and also shows a cylindrical dielectric guide and the movable Faraday probe.

An attempt was made to measure the beam current and arrival time of the propagating front using small magnetic loops mounted on the outside of the dielectric guide. This measurement was not successful because electrical noise picked up on the loops completely obscured any signal induced by the propagating beam. It is likely that this interference originated in the field-emission diode, although noise generated at the surface of the guide by the processes of plasma formation may also have been a major contributor.

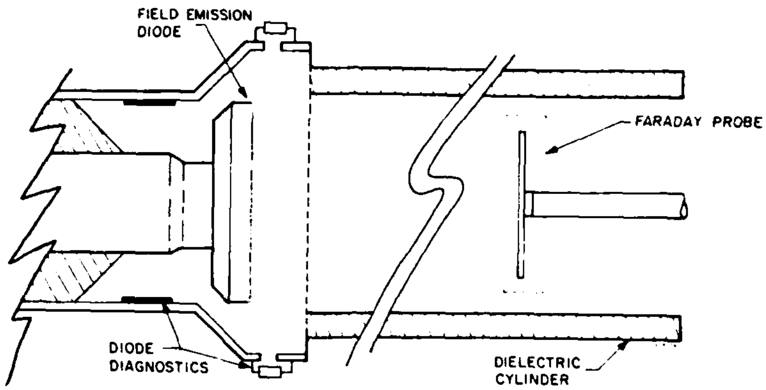


FIGURE 2-1. SCHEMATIC OF FIELD-EMISSION DIODE AND DIAGNOSTICS

2.1.3 Dielectric Guides

Cylindrical guides of two materials and various diameters and lengths and a conical guide were used in the beam propagation experiments. Table 2-2 gives the characteristics of the guides used in these experiments.

The material of the cast epoxy guides, E&C Stycast 1264, has a dc dielectric strength greater than 3 MV/cm and a high-frequency dielectric constant of 3.3.

The guides were mounted in an aluminum vacuum chamber which is an extension of the vacuum housing for the diode of the accelerator. The anode end of the guides must be held in close mechanical contact with the anode mesh to assure good injection of the beam into the guide. In cases where there was poor contact, tracking was observed across the surface of the dielectric to the grounded anode support, and low currents were registered on the Faraday probe.

TABLE 2-2. DIELECTRIC GUIDES USED IN BEAM PROPAGATION EXPERIMENTS AT SPIRE

CYLINDRICAL

Material	I.D. (cm)	Wall (cm)	Length (cm)
Epoxy*	6	1.3	3.6
Epoxy*	6	1.3	20
Lucite (Poly-methylmethac-rylate)	8.3	0.6	30

CONICAL

Material	I.D. (cm)		Wall (cm)	Length (cm)
	Inlet	Outlet		
Epoxy*	6.7	1.3	1.0	20

*Stycast 1264, Emerson and Cuming, Inc., Canton, MA.

2.1.4 Results

Figure 2-2(a) shows typical diode voltage and current traces for experiments with a 3.8-cm-diameter cathode and a 3.5-mm anode-cathode gap. At an initial charging voltage of 300 kV, the diode impedance is nearly matched to that of the 9-ohm line. The anode mesh had an optical transparency of 78 percent for these experiments, and if we assume that this fraction of the diode current was transmitted, then about 12 kA of electrons with an energy of 145 keV were injected into the guide.

Figure 2-2(b) shows recordings of the current measured by the Faraday probe at positions of 2 cm and 15 cm from the anode in the cylindrical epoxy guide of 6-cm diameter and 20-cm length. The long "tail" of the current pulse at the 2-cm position probably is caused by electrons from the background plasma which penetrate the 6-micrometer aluminum foil through small holes.

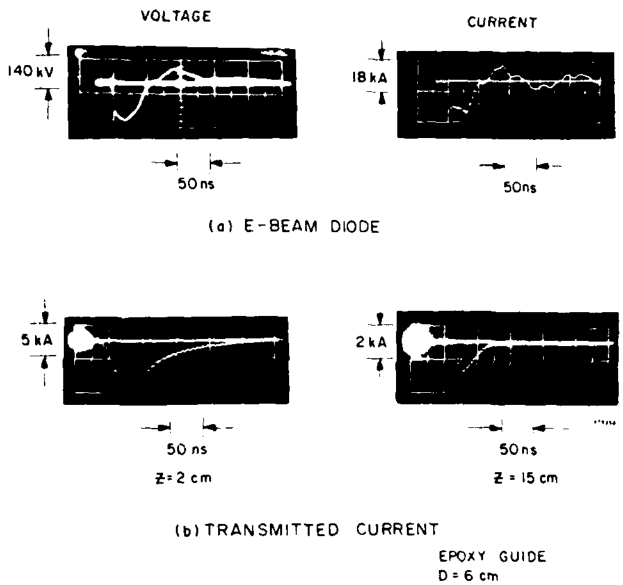


FIGURE 2-2. (a) DIODE VOLTAGE AND CURRENT OF SPI-PULSE 600 UNDER TYPICAL EXPERIMENTAL CONDITIONS AND (b) TRANSPORTED BEAM CURRENT AT POSITIONS OF 2 cm AND 15 cm DOWN GUIDE

It can be seen in Figure 2-2(b) that the transmitted current pulse is shortened by beam-front erosion and the peak current is reduced by about a factor of four between the 2-cm and 15-cm positions.

In earlier experiments, Spire and other groups found that beam-front erosion represented the principal loss of charge from the transmitted beam, and nearly all the injected current was transmitted behind the beam front. Further evidence of this discrepancy is discussed in Section 2.1.4.2.

2.1.4.1 Beam-Front Velocity

<u>Cylindrical Guides</u>

A series of experiments was conducted to test the dependence of the beam-front velocity on electron energy and other experimentally controllable parameters. The beam energy was varied both by changing the charging voltage on the accelerator and by varying the impedance of the diode.

Figure 2-3 shows the arrival time of the beam front as a function of the axial position of the Faraday probe in a 20-cm-long by 6-cm-diameter cylindrical epoxy guide. The beam energy was varied by changing the charging voltage on the accelerator from 150 kV to 400 kV. The diode was operated with a 3.8-cm-diameter cathode and a 3.5-mm anode-cathode gap. The maximum current injected into the guide for the 190-keV beam was 17 kA; the maximum current at 73 keV was 5.5 kA.

The effect of varying the current injected into the dielectric guide was studied by reducing the transparency of the anode mesh of the accelerator diode. A constant charging voltage of 300 kV was used in these experiments, and the diode parameters were the same as for Figure 2-3. The results of this test are plotted in Figure 2-4, showing no significant difference in the velocity of propagation of the beam front for variations of the injected electron current of almost a factor of two. Changing the diameter of the guide or the guide material similarly caused no significant changes of the speed of propagation.

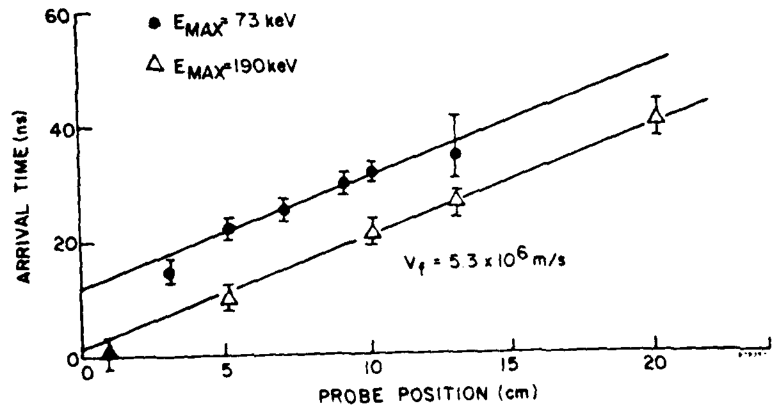


FIGURE 2-3. BEAM-FRONT ARRIVAL TIME VERSUS POSITION OF FARADAY PROBE IN CYLINDRICAL EPOXY GUIDE FOR TWO ELECTRON INJECTION ENERGIES

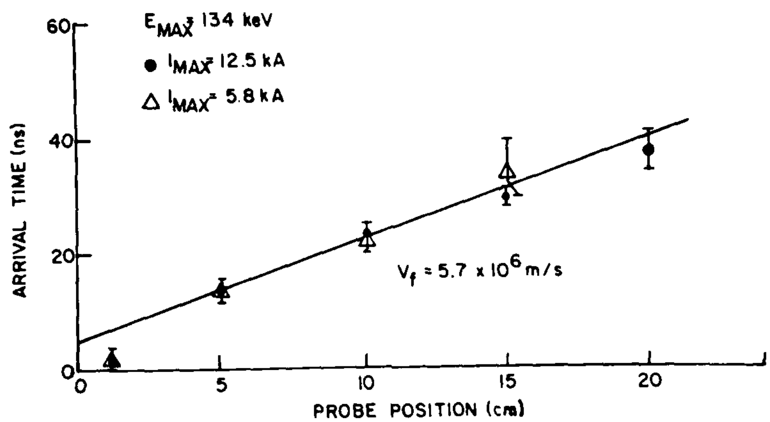


FIGURE 2-4. BEAM-FRONT ARRIVAL TIME VERSUS PROBE POSITION IN CYLINDRICAL EPOXY GUIDE FOR TWO VALUES OF INJECTED CURRENT

Shortened Cylindrical Guide

As a test of the influence of the length of the guide on electron beam propagation, the cylindrical epoxy guide was cut to a length of 3.6 cm, and beam-front arrival times measured as a function of axial position. Experiments were made with a 300-kV initial charging voltage and diode parameters which produced a maximum electron energy of 140 keV and an injected current of 16 kA.

Figure 2-5 shows the arrival time of the beam front as a function of Faraday probe position for the 3.6-cm-long epoxy guide; for comparison, the data on Figure 2-4 for the 20-cm-long guide are repeated in this figure. The propagation speed of the front considerably downstream from the end of the shortened guide is about the same as when the walls of the guide are present. Similar experiments were conducted with higher energy, lower current electron beams launched into short guides which again showed that the speed of propagation of the beam front did not depend on the presence of the dielectric walls of the guide.

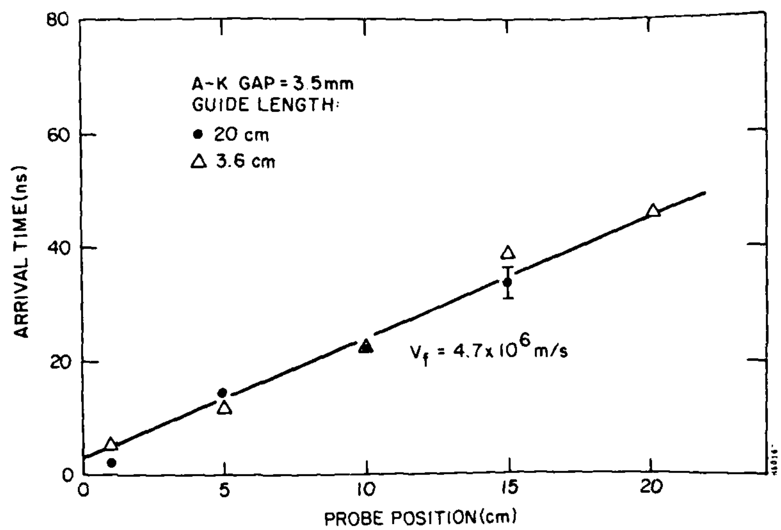


FIGURE 2-5. BEAM-FRONT ARRIVAL TIME VERSUS PROBE POSITION IN LONG AND SHORT GUIDES

Converging Conical Guide

Beam-front arrival times were measured as a function of axial position in a conical guide, which converged from a diameter of 6.7 cm to 1.3 cm in a distance of 20 cm. Figure 2-6 shows the arrival times of the beam front in the conical guide for an accelerator charging voltage of 300 kV, a 3.8-cm-diameter cathode and anode-cathode gaps of 3.5 mm and 7 mm. Under these conditions the propagation speed was about 4×10^6 m/s, regardless of gap setting.

2.1.4.2 Electron Current Propagation

Measurements of current propagation in the dielectric guides were complicated by three factors. First, the Faraday probe collected not only the transmitted electron beam but also electrons from the low-energy plasma formed at the walls of the guide. This spurious signal was largely suppressed by a 6-micrometer grounded aluminum foil placed over the collector of the probe, as indicated in Figure 2-1, although some leakage current was detected when the probe was placed close to the anode mesh. Second, a considerable amount of the electron beam current can be lost through surface discharges across the

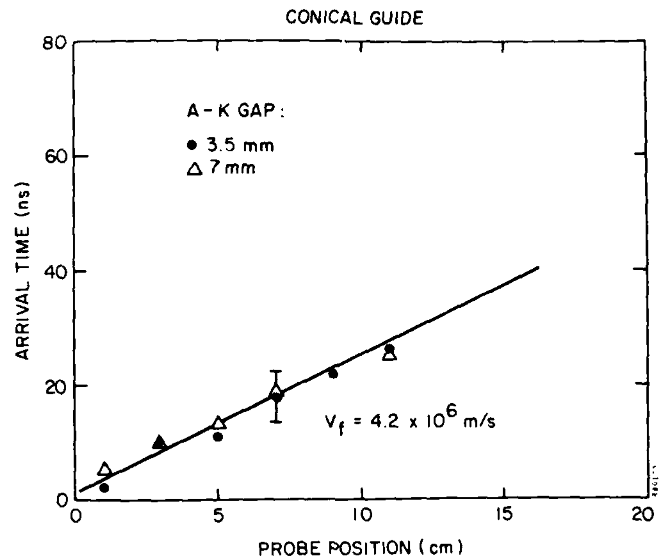


FIGURE 2-6. BEAM-FRONT ARRIVAL TIME VERSUS PROBE POSITION IN CONVERGING CONICAL GUIDE

anode end of the guide when the dielectric is not in good physical contact with the anode mesh. It was found that, although beam-front arrival times were quite reproducible from one experimental setup to another, measurements of the transmitted current were not reproducible if the apparatus was disturbed between experiments. Reasonably consistent measurements of transmitted beam current could be made if the guide and diode were not disassembled during a series of experiments. Third, the presence of the Faraday probe at positions less than 3 or 4 cm from the anode caused perturbations of the current flow under some conditions. This effect was particularly evident for beams accelerated in high-impedance diode configurations. As an example, Figure 2-7 shows the peak transmitted current measured during experiments in which 180 keV, 9 kA beams were injected into 6-cm-diameter cylindrical epoxy guides.

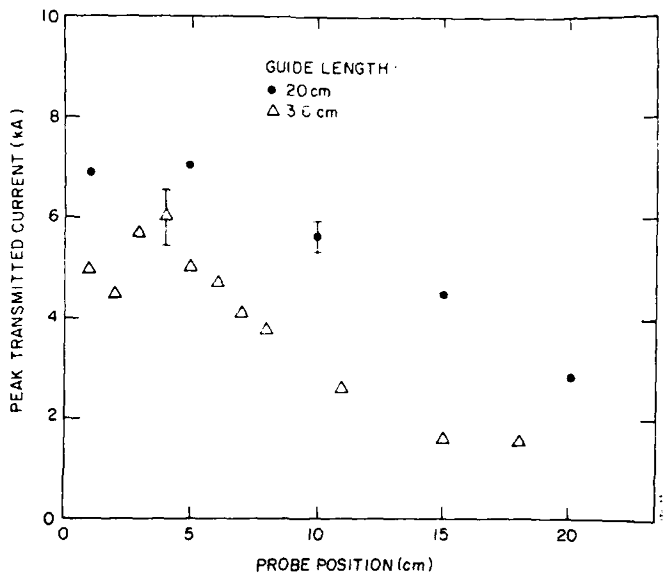


FIGURE 2-7. PEAK TRANSMITTED BEAM CURRENT VERSUS POSITION OF FARADAY PROBE IN CYLINDRICAL EPOXY GUIDES

The lack of reproducibility of the measurements of transmitted current between experimental setups led us to plot the peak transmitted current normalized to the current measured at a probe position of 1 cm from the anode. Figure 2-8 shows this plot for the cylindrical epoxy guides of 3.6-cm and 20-cm lengths and for the convergent conical guide. An initial charging voltage of 300 kV and a diode of 3.8-cm diameter and 3.5-mm gap were used for the accelerator.

The normalized propagating current appears to follow an approximately exponential decrease with distance down the guide. The dashed curve in Figure 2-8 illustrates a law of the form,

$$\frac{I(z)}{I(1\ \mathrm{cm})} = \exp\left(-\frac{z - 1\ \mathrm{cm}}{7.4\ \mathrm{cm}}\right) \tag{2.1}$$

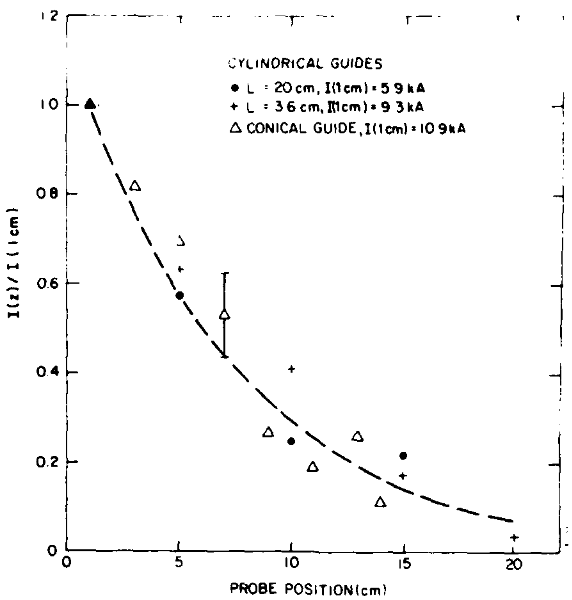


FIGURE 2-8. NORMALIZED TRANSMITTED BEAM CURRENT VERSUS PROBE POSITION IN EPOXY GUIDES

The loss of beam current with guide length occurs in spite of evidence of pinching of the propagating electron beam. Figure 2-9 shows the damage to the 6-micrometer aluminum foil shield of the Faraday probe after one shot from the electron beam. The probe was located at a distance of 2 cm from the anode for this shot, although similar evidence of beam pinching was observed at all axial positions and all accelerator conditions.

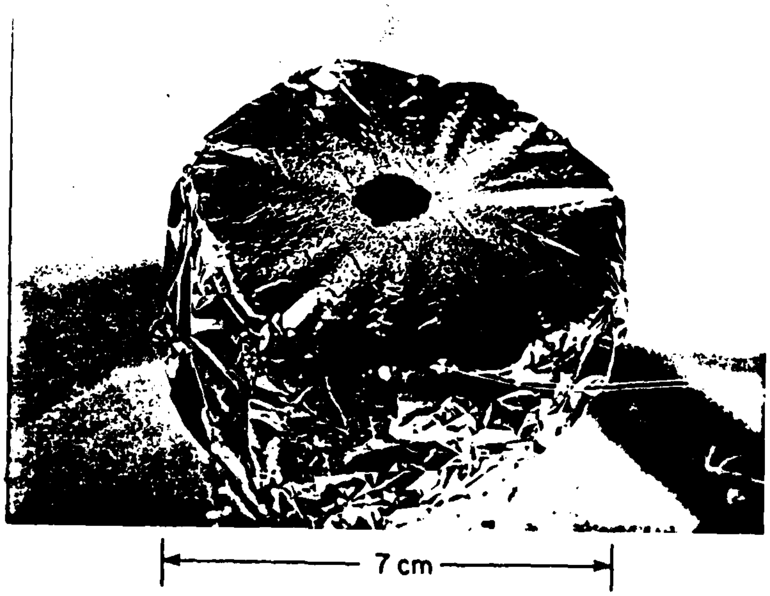


FIGURE 2-9. DAMAGE TO ALUMINUM SHIELD OF FARADAY PROBE

2.2 EXPERIMENTS AT NRL

A 5-day experiment was conducted at the Naval Research Laboratory in August 1980 with an accelerator capable of injecting electron beams considerably greater than the Alfven limit into dielectric guides. The principal objective of the experimental program was to study collective ion acceleration, although some information was gathered on electron beam propagation.

The high-current beam from the accelerator destroys the anode structure of the field-emission diode on each shot. The replacement of the anode and other preparations limits the shot rate to about one per hour. For this reason, only a narrow range of parameters could be investigated during the experimental period.

2.2.1 Electron Accelerator

The experiments were conducted with the Gamble I pulsed electron beam accelerator(17) shown in Figure 2-10. This machine uses a 30-stage Marx generator to pulse-charge a low-inductance water transfer capacitor; at the peak of the charging cycle, the transfer capacitor is connected to a 4-ohm, 33-ns coaxial water pulse-forming line through a triggered spark switch. At the peak of its charging cycle, the pulse-forming line is switched into a 4- to 1.5-ohm impedance-transforming water line by a low-inductance, triggered switch. The output of the line is connected to the vacuum diode to produce 70-ns electron beam pulses with total energies up to 20 kJ.

2.2.2 Diagnostics

The beam voltage is monitored by a capacitive pickup in the water line of Gamble I and corrected for inductive voltage drop by a magnetic dI/dt loop in the vacuum diode region. The magnetic loop signal is integrated to obtain the current waveform and can be compared with the signal from a return-current shunt in the anode plane.

The transmitted beam current and energy were measured by a 10-cm-diameter carbon Faraday cup-calorimeter. The Faraday cup is shunted by a 1.64 mohm resistance, and its output displayed directly on an oscilloscope. The thermocouple output of the calorimeter is displayed by a strip-chart recorder.

The Faraday cup-calorimeter was mounted in the vacuum chamber approximately 5 mm downstream from the exit of the dielectric guides. The nuclear activation foils used to detect high-energy collectively accelerated ions were attached directly or mounted on an aluminum holder fastened to the carbon disk of the calorimeter.

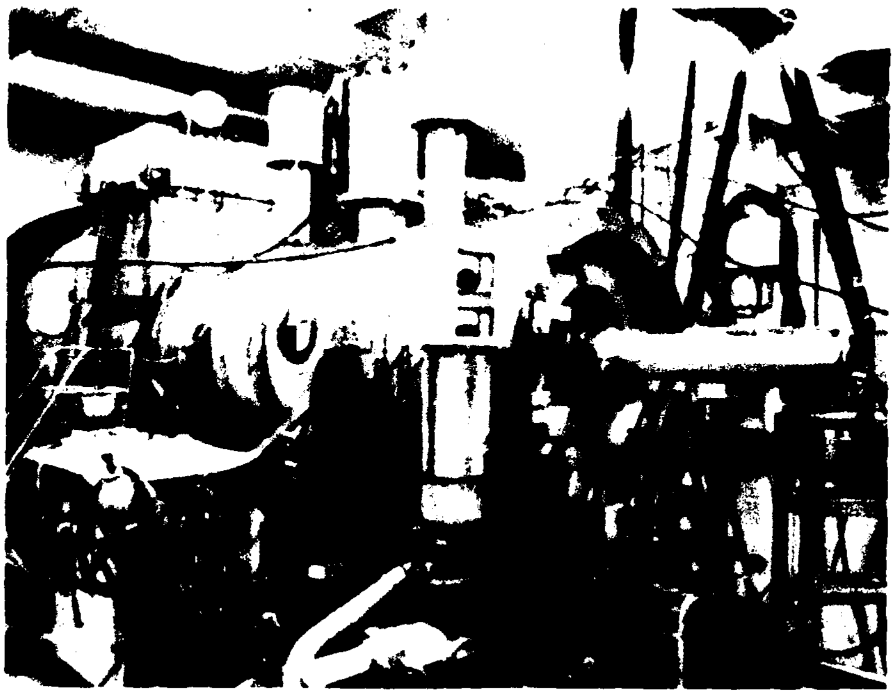


FIGURE 2-10. DIODE END OF GAMBLE I ACCELERATOR AND EXPERIMENTAL APPARATUS

R81023P

Calorimeter measurements were corrected for the thermal capacity of the foils and holder, although there was poor thermal contact between the carbon and the activation foils for several shots. We believe that the calorimeter was the least reliable of the transmitted beam diagnostics.

2.2.3 Experimental Arrangement

Three cylindrical dielectric guides were used in the experiment. They were all made of Lucite acrylic with outside and inside diameters of 8.89 cm and 7.62 cm, respectively. The guides had lengths of 30.5, 61.0, and 91.4 cm, although the majority of shots were made with the 30.5-cm long guide.

The acrylic guides were mounted inside the evacuated cylindrical chamber shown in Figure 2-10 on the diode end of Gamble I. The inlet of the guide was pressed flush against the anode of the vacuum diode and concentric with the accelerator cathode. It was found during early shots that the inlet end of the guides was severely damaged by surface flashover. A 0.3 mm thick by 6.4 mm wide graphite ring was then glued to the end of the guide to provide a conduction path for the beam electrons which caused this flashover. The graphite ring significantly reduced the damage to the end of the guide and greatly improved the reproducibility of the experimental results.

The diode configurations used in the experiment are summarized in Section 3.2. They ranged from annular cathodes with a 7 cm OD and 5 cm ID to 1.27 cm diameter solid cathodes. Most experiments were conducted with 6.3 micrometer thick aluminized Mylar foil anodes, with the aluminized side facing the cathode. A few shots were conducted with stainless steel mesh anodes or with 17.8 micrometer thick aluminum foil.

2.2.4 Results

The principal objective of the experiment at NRL was to study collective ion acceleration, and only a limited number of shots could be performed during the 5-day period of the experiment. For this reason, the investigation of electron beam propagation was given secondary importance during the program at Gamble I.

One series of shots was conducted over a broad enough range of experimental parameters to show a clear trend of results. In this 5-shot series using a 25.4 mm diameter cathode, the anode-cathode gap was progressively decreased from 8 to 5 mm while holding other experimental parameters constant. Figure 2-11 shows the diode current and Faraday cup current recorded at the end of the 30.5 cm guide at the time of the peak diode voltage.

The peak voltage on the diode and other experimental parameters are summarized in Table 2-3. Although the peak voltage decreases as the injected current increases, there is a clear proportionality between the transmitted and current injected into the guide.

Also shown on Figure 2-11 is the Alfven limiting current at the peak of the voltage pulse, computed from the formula,

$$I_A = 17\sqrt{\gamma^2-1} \quad \text{(KA)} \tag{2.2}$$

where I_A is in kiloamperes and γ is the relativistic energy parameter of the electrons,

$$\gamma = 1 + \frac{eV}{mc^2} \tag{2.3}$$

eV and mc^2 are respectively the kinetic energy and rest mass of the accelerated electrons.

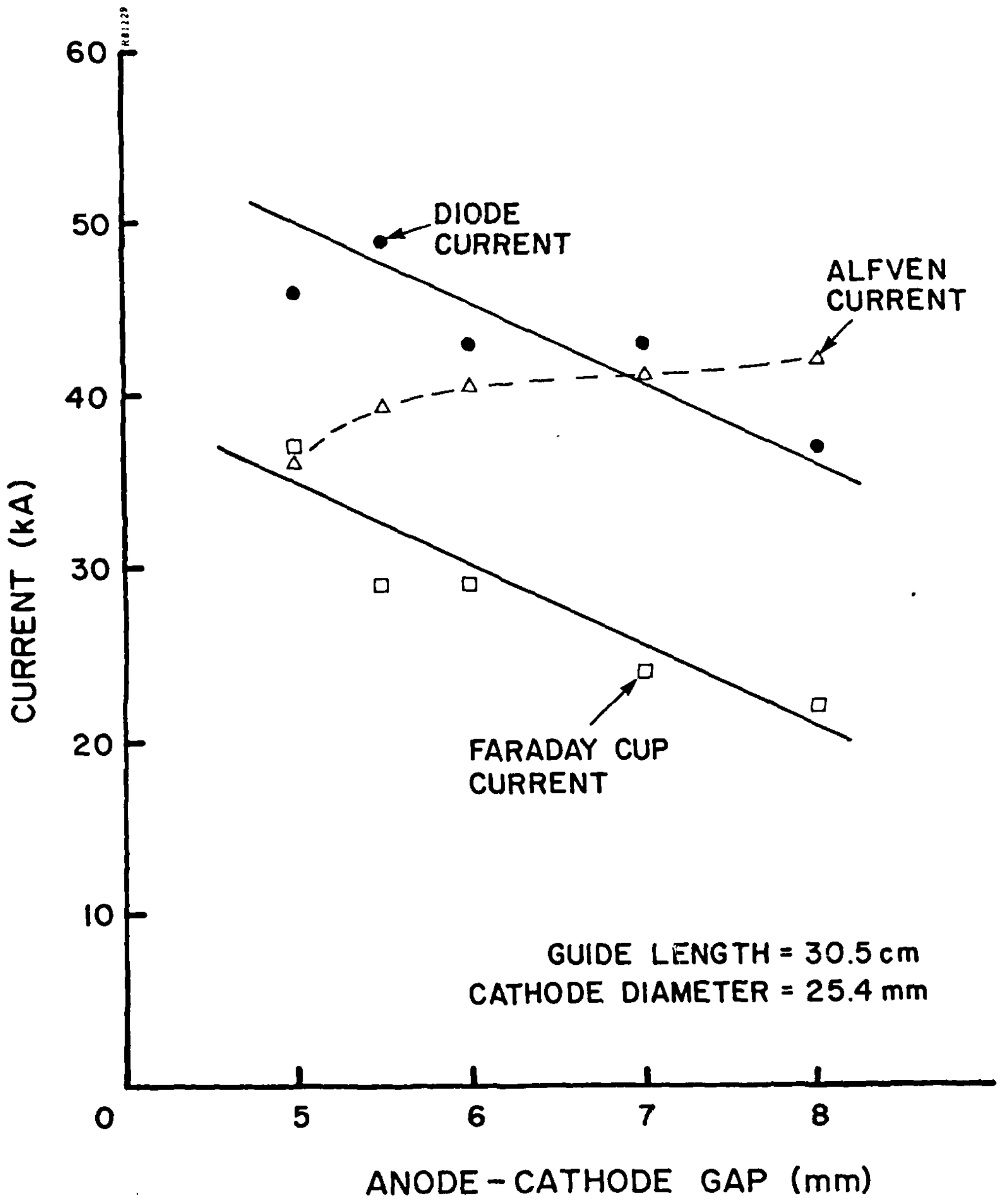


FIGURE 2-11. DIODE, TRANSMITTED AND ALFVEN LIMITING CURRENTS AT PEAK OF VOLTAGE PULSE

TABLE 2-3. EXPERIMENTAL PARAMETERS OF CURRENT TRANSMISSION EXPERIMENTS

Shot No.	A-K Gap (mm)	V_{MAX} (kV)	I_{DIODE} (kA)	I_{ALFVEN} (kA)	$I_{FARADAY}$ (kA)
16	8	854	37	42.1	22
17	7	831	43	41.3	24
18	6	809	43	40.5	29
20	5.5	786	49	39.7	29
19	5	704	46	36.7	37

Cathode Diameter = 25.4 mm

Guide Length = 30.5 cm

It can be seen in Figure 2-11 that, although the injected diode current was greater than the Alfven limit for several of the shots, the transmitted current recorded at the Faraday cup was less than or equal to the Alfven value.

A few shots were performed using the 61 cm and 91.4 cm long guides. The transmitted current measured by the Faraday cup for shots with each of these guides is shown in Figure 2-12. The diode voltage and current were the same as shot No. 20 shown on Table 2-3. A clear beam-front arrival is seen in Figure 2-12(a) with the 61 cm guide, although none is apparent for the 91.4 cm guide.

When we compared the arrival times of the beam front between the 30.5 and 61 cm guides, we found an average beam-front velocity of about 1.5×10^7 m/s. A proton with this velocity would have an energy of about 1.2 MeV. The accuracy of the velocity measurement, however, is not better than about $\pm 50\%$, because only three shots were made with the 61 cm guide.

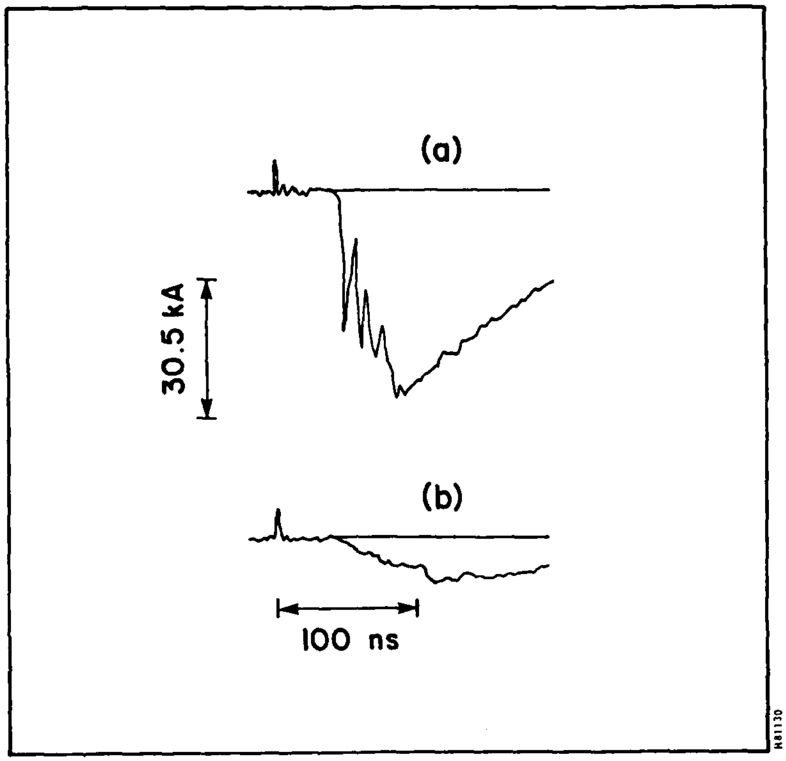


FIGURE 2-12. FARADAY CUP CURRENT RECORDED AT END OF (a) 61 cm LONG GUIDE; (b) 9.14 cm LONG GUIDE

SECTION 3

COLLECTIVE ION ACCELERATION EXPERIMENTS

3.1 EXPERIMENTS AT SPIRE

In Spire's earlier experiments,[3,4] as many as 10^{11} protons per pulse were observed to be accelerated to energies up to six times the maximum electron beam energy. These results were obtained using the SPI-PULSE 6000 electron accelerator, which produces a linearly increasing beam current for approximately 80 ns. During this time, the diode voltage is almost constant, or decreasing slightly near the peak of the current pulse.

In the recent experimental series, the higher impedance, shorter pulse length SPI-PULSE 600 electron accelerator was used to investigate collective ion acceleration under rather different pulse conditions. The accelerator and its typical electron beam output are described in Section 2.1.

No significant collective ion acceleration was observed over a fairly broad range of beam and guide conditions using the SPI-PULSE 600 accelerator. These experiments are summarized below.

3.1.1 Experimental Configuration

The dielectric guides tested for ion acceleration are listed in Table 3-1. As in the measurements of beam propagation, the inlet end of the guide was pressed against the anode mesh of the accelerator diode. Various cathode diameters and anode-cathode gap spacings were used in the experiments. The electron accelerator was charged to either 300 or 400 kV, and the peak voltage and electron current were as described in Section 2.1.

The same time-of-flight diagnostics used in Spire's earlier work[3,4] were used to search for collectively accelerated ions in this series of experiments. An aluminum plate with a 12.7 mm diameter aperture was placed at the exit end of the dielectric guide under test. A 500 gauss permanent magnet, 2 cm long, was mounted on the plate behind the aperture, followed by a second 12.7 mm aperture. The magnet deflects the electron beam and allows only energetic ions to propagate through the aperture. The ions are detected on a 50 percent transmitting mesh and a biased Faraday cup 20 cm downstream from the mesh.

TABLE 3-1. DIELECTRIC GUIDES USED IN ION ACCELERATION EXPERIMENTS AT SPIRE

CYLINDRICAL

Material	I.D. (cm)	Wall (cm)	Length (cm)
Epoxy*	6.0	1.3	3.6
Epoxy*	6.0	1.3	16.4
Epoxy*	3.9	1.6	18.3
Lucite (Poly-methylmethacrylate)	7.7	0.6	22.9

CONICAL

Material	I.D. (cm)		Wall (cm)	Length (cm)
	Inlet	Outlet		
Epoxy*	6.7	1.3	1.0	20

*Stycast 1264, Emerson & Cuming, Inc., Canton, Massachusetts.

Because of the negative results of the experiments, several modifications of the ion collector were used in attempts to increase the sensitivity of ion detection. These included removal of the ion collector mesh, the placement of the Faraday cup only 1 to 2 cm downstream from the magnet structure, increasing the aperture of the detector, variation of the magnetic field strength, and moving the aluminum baffle and detector structure as far as 50 cm from the exit end of the dielectric guide. It was found that increasing the aperture of the detector or reducing the electron deflector magnetic field allowed transmitted beam electrons to enter the Faraday cup. None of these modifications results in the detection of accelerated ions.

3.1.2 Results

The background noise level for the ion acceleration experiments was typically 25 to 50 mV into the 50 ohm input of the recording oscilloscope. This corresponds to a minimum observable ion current of 0.5 to 1 mA at the Faraday cup. The aperture area of the magnet structure was usually about 5 percent of the cross-sectional area of the dielectric guides, so that total ion currents greater than 10 to 20 mA should be observable with the ion detection apparatus.

Cylindrical Guides

The cylindrical epoxy guides with inside diameters of 3.9 and 6.0 cm and lengths between 3.6 and 18.3 cm were tested for ion acceleration with a variety of beam conditions. Both high and low impedance diodes were used. In the high-impedance configuration, the injected current at peak acceleration voltage of 190 kV was 10 kA; the low impedance diode produced an electron beam of 120 kV peak voltage at a current of 30 kA.

The Lucite guide was tested with a hollow cylindrical beam formed by an annular cathode with a 76 mm OD and 38 mm ID. A beam with a peak voltage of 168 kV and a current of 32 kA was injected into this guide.

No observable ion current was detected with any of the cylindrical guides. This was true with the magnet aperture and Faraday cup both directly at the exit of the guide and downstream as far as 50 cm.

Conical Guide

The converging conical guide was tested for ion acceleration using an electron beam with 180 kV peak voltage and 9 kA current at the voltage peak. The magnet aperture plate was mounted directly at the exit of the guide. No collectively accelerated ions were detected above the noise which represented a minimum detectable ion current of 0.5 to 1 mA.

3.2 EXPERIMENTS AT NRL

The principal purpose of the experiments at the Naval Research Laboratory was to investigate collective ion acceleration in dielectric guides under conditions very different from those at Spire or in other experiments. In particular, we wished to investigate the variation of ion energy with beam current density and guide length with beam currents approaching and greater than the Alfven limiting current.

The Gamble I accelerator at NRL used for these experiments is described in Section 2.2.1. This 1.5-ohm accelerator was chosen for its ability to accelerate very high current electron beams. The cylindrical Lucite acrylic guides described in Section 2.2.3 were used in this experiment. Most shots were performed using the 30.5 cm long guide.

3.2.1 Diagnostics

Nuclear activation techniques(18) were used to detect collectively accelerated ions, estimate their number and measure their energy. A rhodium-activation counter(19) with a polyethylene moderator was used to detect neutrons generated by the reactions shown in Table 3-2. The principal sources of neutrons were p,n reactions with copper in the activation targets mounted on the face of the Faraday cup-calorimeter (see Section 2.2.2). Another source of neutrons is reactions between accelerated deuterons and ^{12}C and ^{16}O. This is a rather small source, since the natural abundance of deuterium is only 0.15%; no deuterated materials were used in the experiment.

The number of accelerated protons and their energy was estimated by measuring the activation in stacks of copper and titanium foils mounted on the Faraday cup calorimeter at the end of the dielectric guide. The nuclear reactions shown in Table 3-3 were used for this diagnostic.

TABLE 3-2. NEUTRON-GENERATION REACTIONS

Reaction	Threshold Energy (MeV)	Remarks
$^{63}Cu(p,n)^{63}Zn$	4.21	^{63}Cu has 69% natural abundance.
$^{65}Cu(p,n)^{65}Zn$	2.17	^{65}Cu has 31% natural abundance.
$^{13}C(p,n)^{13}N$	3.23	^{13}C has 1.1% natural abundance
$^{12}C(d,n)^{13}N$	0.33	Very low n yield below 0.6 MeV
$^{16}O(d,n)^{17}F$	1.83	
$D(d,n)^{3}He$	—	D has 0.015% natural abundance.

TABLE 3-3. NUCLEAR-ACTIVATION REACTIONS

Reaction	Threshold Energy (meV)	Product Half Life	Remarks
$^{63}Cu(p,n)^{63}Zn(\beta^{+})^{63}Cu$	4.21	38.5 min	^{63}Cu has 69% natural abundance
$^{65}Cu(p,n)^{65}Zn(\beta^{+})^{65}Cu$	2.2	243.7 day	^{65}Cu has 31% natural abundance.
$^{47}Ti(p,n)^{47}V(\beta^{+})^{47}Ti$	3.78	33 min	^{47}Ti has 7.3% natural abundance.
$^{48}Ti(p,n)^{48}V(\beta^{+})^{48}Ti$	4.90	160 day	^{48}Ti has 73.9% natural abundance.

Nuclear reactions producing positron emitters were chosen for the activation measurements. After activation, the target was placed between two sodium-iodide detectors with a pulse-height discriminator and a coincidence circuit set to detect only pairs of 0.51 MeV gamma rays from positron annihilation.[18] In practice, only the p,n reactions with ^{63}Cu and ^{47}Ti with short half-lives produce strong enough positron emission to be useful for the level of energetic protons produced in this experiment.

The energy of the incident particles was estimated by the thickness of the foils penetrated and activated by the protons. Figure 3-1 shows the effective range of protons in copper and titantium as a function of incident energy.[20] The nuclear activation as a function of depth in the foil stack then can be related to the energy spectrum of the incident particles.[21,22]

Initial ion acceleration experiments were conducted with 0.254 mm thick (10 mil) copper target foils, approximately 6 cm square, mounted directly on the carbon surface of the Faraday cup-calorimeter. Later shots were performed with stacks of 0.050 mm thick copper and 0.025 mm thick titanium foils, about 7x7 cm square, mounted on an aluminum holder plate.

3.2.2 Results

During the five-day experimental period, a total of 31 shots were made on the Gamble I accelerator. Of these, seven were performed to characterize the beam from the accelerator without a dielectric guide. The Faraday cup-calorimeter and diode diagnostics were used to establish the voltage and current injected directly from the diode.

Hollow Beams

A hollow beam was used in initial shots since higher current densities theoretically can be propagated in a thin cylindrical shell than in a solid cylindrical configuration.[23]

An annular cathode with an OD of 70 mm and an ID of 50 mm was used to inject electron beam currents between 46 and 62 kA into the 30.5 cm long guide. Table 3-4 shows the parameters of the electron beams at the peak of the voltage and current pulse for the shots using hollow beams. No nuclear activation by collectively accelerated ions was observed for the shots with hollow electron beams.

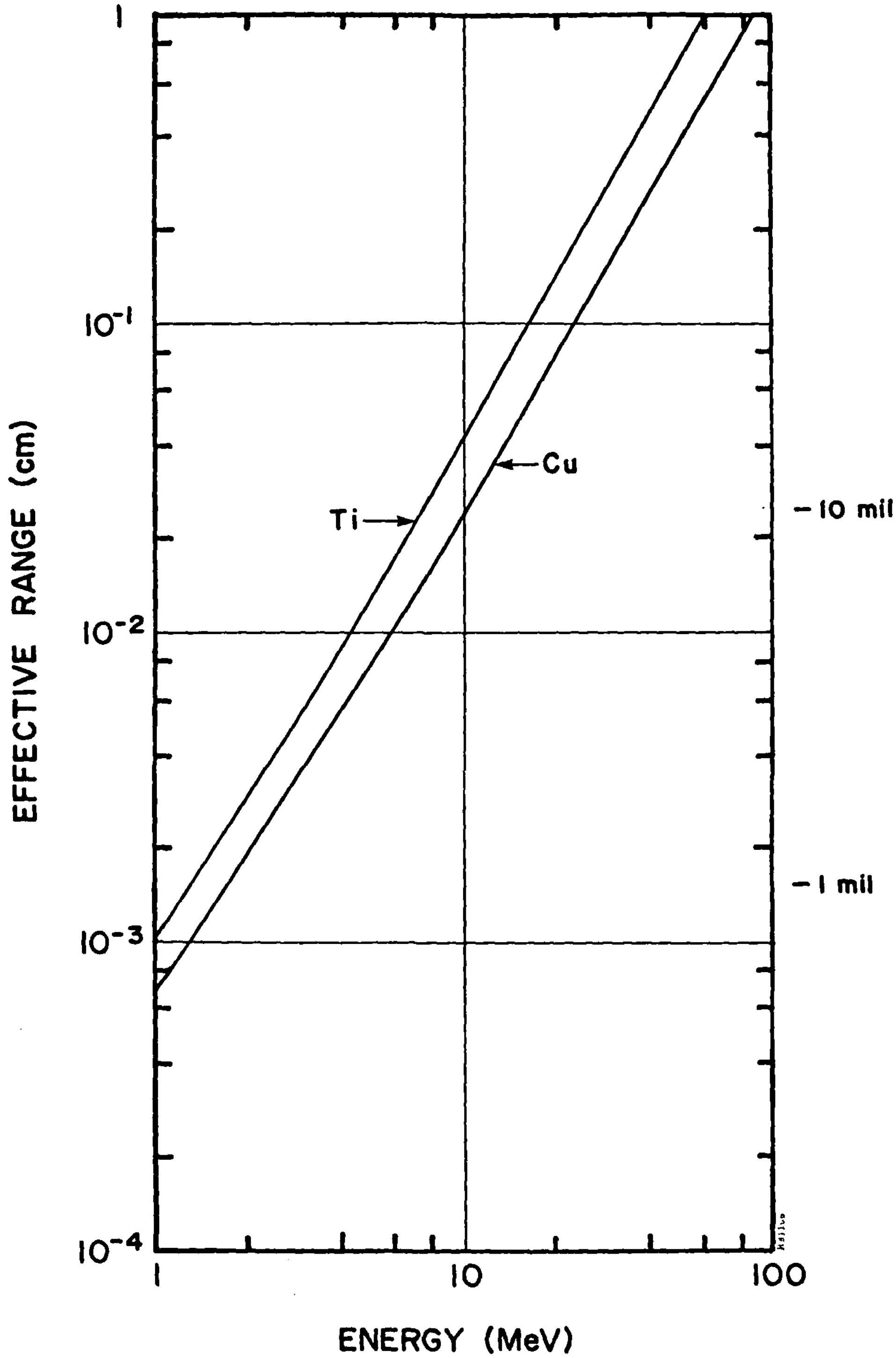


FIGURE 3-1. RANGE OF PROTONS IN COPPER AND TITANIUM

TABLE 3-4. BEAM PARAMETERS FOR SHOTS WITH HOLLOW BEAM

Shot No.	V_{max} (kV)	I (kA)	I_{FC} (kA)	Remarks
8	689	46	18	V_{Marx} = 55 kV
9	839	49	*	V_{Marx} = 55 kV
10	824	62	12	V_{Marx} = 60 kV
		Guide Length = 30.5 cm		

*Oscilloscope photo unreadable.

Cylindrical Beams

The lack of collective ion acceleration with hollow beams led us to use solid circular cathodes with diameters between 12.7 mm and 70 mm. Most of the shots were conducted with 12.7 mm and 25.4 mm diameter cathodes. The highest yields of collectively accelerated ions were observed using the 25.4 mm diameter cathode. Figure 3-2 shows the decay of the β^+ emission of a 9.4 gm copper target activated by accelerated protons. The 38 minute half-life of the emission clearly shows that the $^{63}Cu(p,n)^{63}Zn$ reaction was the source of the nuclear activation.

Table 3-5 summarizes results for shots with solid cathodes and aluminized mylar anodes. The neutron yields measured by the rhodium and β^+ detectors were projected back to the time of the shot using the formula,

$$N_o = \frac{C_{12} - B_{12}}{\epsilon\left(e^{-t_1/\tau} - e^{-t_2/\tau}\right)} \qquad (3.1)$$

where t_1 (t_2) are the time elapsed after the shot before starting (ending) counting. C_{12} is the measured count, B_{12} is the background, ϵ is the detector efficiency, and τ is the decay constant of the activated isotope.

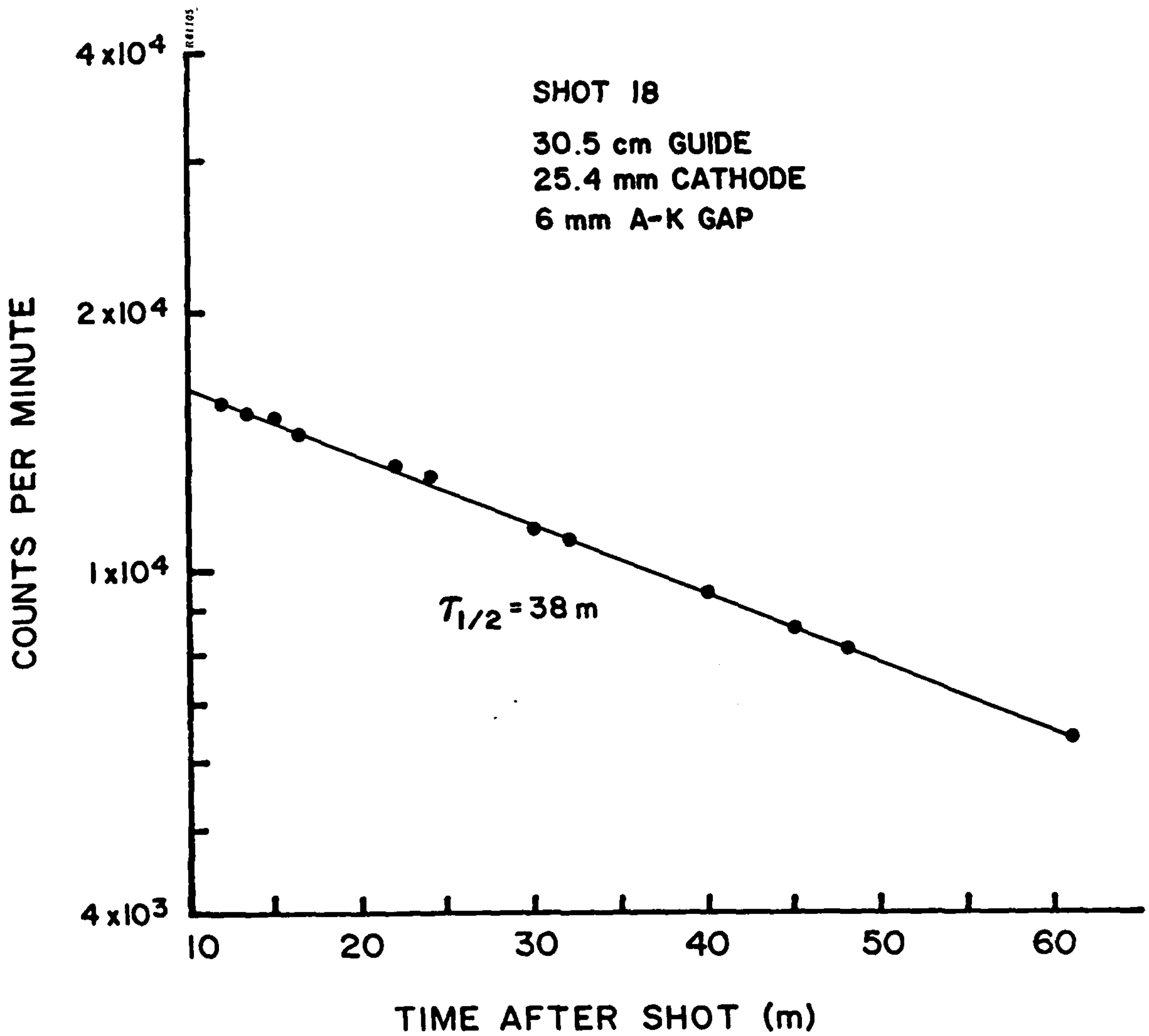


FIGURE 3-2. DECAY OF POSITRON EMISSION RATE FROM ACTIVATED COPPER TARGET

TABLE 3-5. ION ACCELERATION WITH CYLINDRICAL BEAMS AND ALUMINIZED-MYLAR ANODES

Shot No.	Guide Length (cm)	Cathode Diam. (mm)	A-K Gap (mm)	V_{max} (kV)	I (kA)	Neutron Yield	^{63}Zn Yield
12	30.5	12.7	4	749	74	2.3×10^6	1.4×10^4
13	30.5	12.7	5	824	37	5.5×10^5	4.8×10^3
14	30.5	12.7	4	734	74	1.3×10^6	*
16	30.5	25.4	8	854	37	Bkg	*
17	30.5	25.4	7	831	43	5.2×10^6	4.7×10^6
18	30.5	25.4	6	809	43	9.1×10^6	1.1×10^7
19	30.5	25.4	5	704	46	1.1×10^6	1.0×10^4
20	30.5	25.4	5.5	786	49	7.7×10^6	5.4×10^6
21	No guide	25.4	5.5	*	52	1.3×10^7	7.3×10^6
24	30.5	70	10	801	62	Bkg	Bkg
27	30.1	25.4	5.5	757	49	4.6×10^6	4.8×10^5
28	61	25.4	5.5	727	49	1.3×10^6	1.5×10^5
29	61	25.4	6	809	43	Bkg	Bkg
30	91.4	25.4	5.5	771	49	2.1×10^5	2.0×10^4

Bkg = Background.

*Data lost because of equipment failure.

The highest neutron yield measured by both the Rh and β^+ detectors occurred for shots with 25.4 mm diameter cathodes, an A-K gap spacing of 5.5 mm, and 30.5 cm long guides. A control shot (Number 21), however, in which the 30.5 cm guide was removed and all the parameters unchanged, showed the highest neutron yield from the Rh detector of any shot in the series. This results was a clear indication that most of the high-energy protons originated in the anode foil.

A few shots were made with stainless steel meshes or 0.18 mm (0.7 mil) thick aluminum foil replacing the aluminized Mylar anodes. Table 3-6 summarizes the results of these shots along with one shot without an anode. The only shots showing significant neutron production and target activation were those with the aluminum foil anodes. We believe that hydrogen from adsorbed water and oil on the foil was the source of the accelerated protons.

Ion Energies

Table 3-7 shows the neutron yield calculated from Equation (3.1) for protons passing through more than one layer of copper foil. In all of these shots the proton energy had to be at least 11.6 MeV to penetrate the 0.254 mm copper foil and produce nuclear reactions in the second layer of foil (see Figure 3-1).

There was no evidence that the length of the dielectric guide influenced the energies of the accelerated ions. Three shots were made with the 60 cm long guide. Both the Rh detector count and the β^+ activation of the top copper foil of the stack decreased by almost a factor of three between nearly identical shots (Nos. 27 and 28) with 30 cm and 60 cm long guides. No activation of the copper in the second 0.050 mm foil was detected for either shot. Accelerator parameters, however, were almost identical to those of earlier shots (e.g., No. 20) which produced activation in two layers of 0.254 mm thick foil.

TABLE 3-6. SHOTS WITH NONSTANDARD ANODES

Shot No.	Anode Type	Cathode Diam. (mm)	A-K Gap (mm)	V_{max} (kV)	I (kA)	Neutron Yield	^{63}Zn Yield
15	Mesh	12.7	4	824	111	Bkg	Bkg
22	None	12.7	5.5	869	40	Bkg	Bkg
23	Mesh	70	10	*	83	$6x10^4$	$9x10^3$
26	Al Foil	25.4	5.5	771	49	$4.4x10^6$	$2.0x10^6$
31	Al Foil	25.4	5.5	771	49	$2x10^5$	Bkg

Bkg = Background.

Guide length = 30.5 cm for all shots except No. 31, which used 61 cm guide.

*Oscillogram illegible.

TABLE 3-7. ACTIVATION FROM PROTONS PENETRATING MULTILAYER TARGETS

Shot No.	Penetrating Depth (mm)	Cathode Diam. (mm)	A-K Gap (mm)	V_{max} (kV)	I (kA)	^{63}Zn Yield
19	0.254	25.4	5.0	704	46	$5x10^3$
20	0.254	25.4	5.5	786	49	$9x10^3$
26	0.254	25.4	5.5	771	49	$1.4x10^4$

Guide length = 30.5 cm.

Energetic Proton Yield

Only a rough estimate can be made for the yield of collectively accelerated protons with energies greater than the 4.2 MeV threshold of the ^{63}Cu(p,n)^{63}Zn reaction. However, if we consider shots in which two layers of copper foil were activated, we can make a rough calculation of the yield of protons accelerated to energies greater than 11.6 MeV.

Shots No. 20 and 26 are the only shots which generated enough activation in multilayer targets to give a rough idea of the energetic proton yield. In both shots, two layers of 0.254 mm thick copper foil were activated to the levels shown in Tables 3-5, 3-6 and 3-7. If we assume that the majority of protons causing activation in the copper have energies of 5 MeV or lower in both layers of foil, we can then use calculations[(24)] of the thick target yield of ^{63}Zn to estimate the number of incident protons. The energy of the protons producing activation in the second layer of foil is estimated by assuming that protons lose all but 5 MeV of their energy in penetrating the first foil. Using the range data of Reference 20, we find an incident energy of 12 MeV.

Table 3-8 shows the estimated high-energy proton yield from shots no. 20 and 26. Although there is not enough data to compare with other experiments, these results are at least consistent with other measurements of collectively accelerated ion spectra (e.g., 8, 13).

TABLE 3-8. ESTIMATED HIGH-ENERGY PROTON YIELD

Shot No.	Proton Yield* E_p = 5 MeV	Proton Yield* E_p = 12 MeV
20	7.2×10^{11}	1.2×10^{9}
26	2.7×10^{11}	1.9×10^{9}

*Based on a ^{63}Zn yield of 7.5×10^{-6} per 5 MeV proton.

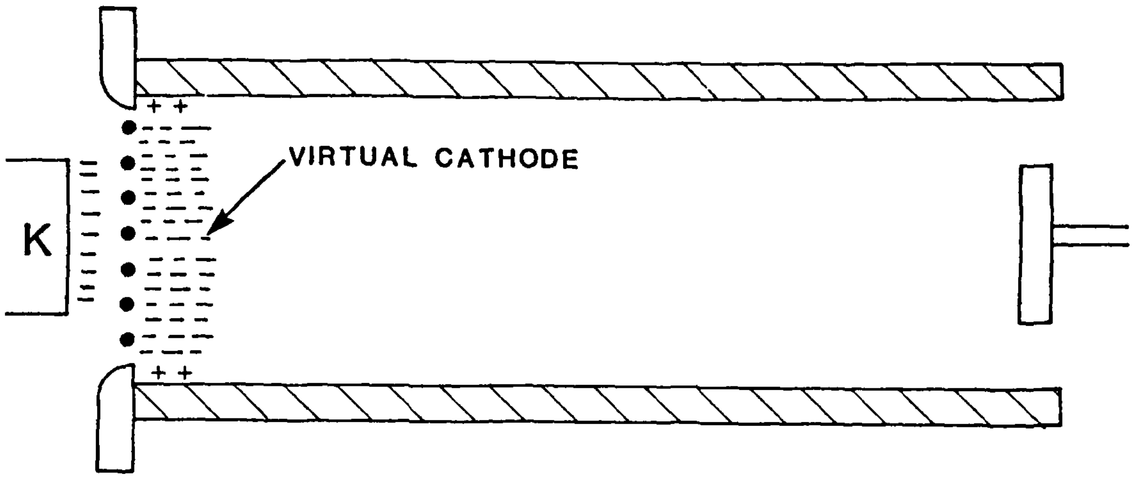
SECTION 4
DISCUSSION

4.1 ELECTRON BEAM PROPAGATION

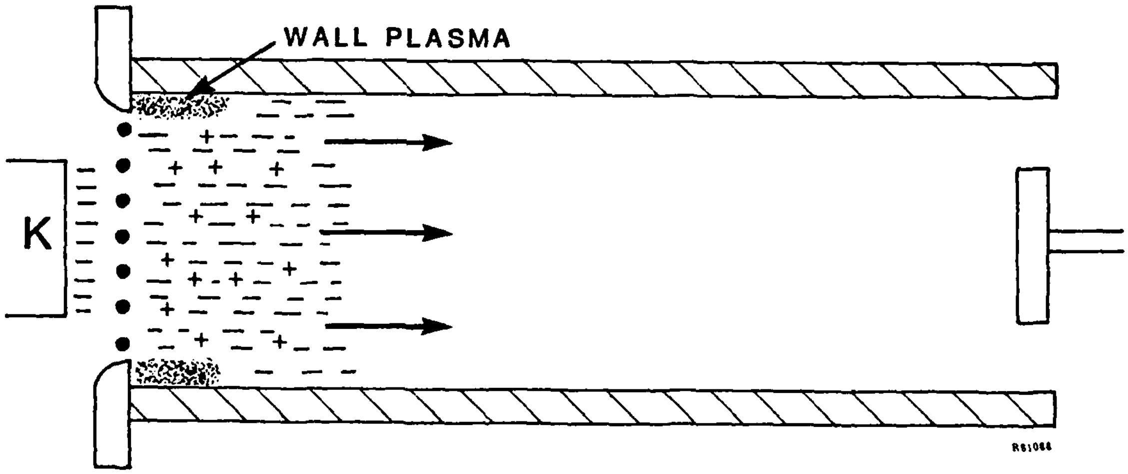
These experiments, both at Spire and NRL, indicate that the processes which determine the velocity of the beam front act principally near the anode, where the electron beam initially forms a virtual cathode. Under the conditions of the experiments, the walls of the guide downstream from the anode do not influence the propagation of the front, although there is clear evidence that the efficiency of current transport is improved when the wall is present.

Figure 4-1 is a model of electron beam propagation in dielectric guides. At the beginning of the pulse (a), the electron beam forms a virtual cathode close to the anode plane and begins to expand radially. Surface flashover and other processes form a plasma at the guide wall, and ions are drawn into the negative space charge well. The electron beam, which is still being accelerated through the anode screen, begins to propagate (b) when the ion density reaches a high enough level to neutralize some of the space charge. The ions are accelerated, essentially dragged by the electronic space charge downstream. It is this acceleration near the anode plane that determines the (constant) speed of the beam front. As shown in (c), the electron beam is reflected at the moving front, and the return current to the anode of the accelerator is made through the wall plasma which has begun to fill the guide. This plasma is formed along the whole length of the guide, as shown by open-shutter photographs.[6] Finally, the electron beam strikes a grounded metallic target (d), and propagates with good efficiency through the plasma released from the walls of the guide. The self-generated magnetic field of the beam causes pinching of the well-neutralized beam.

The apparent independence of the beam-front velocity from the conditions downstream of the inlet to the dielectric guide is similar to the behavior of experiments with Luce diodes and other high-current, pulsed electron accelerators in which a dielectric material or gas is placed in the anode region to provide space charge neutralization.[11,12,13,14,15] Several experiments of this type show that the beam propagates as a sharply defined front associated with energetic ions accelerated to the electron energy or a few times greater.

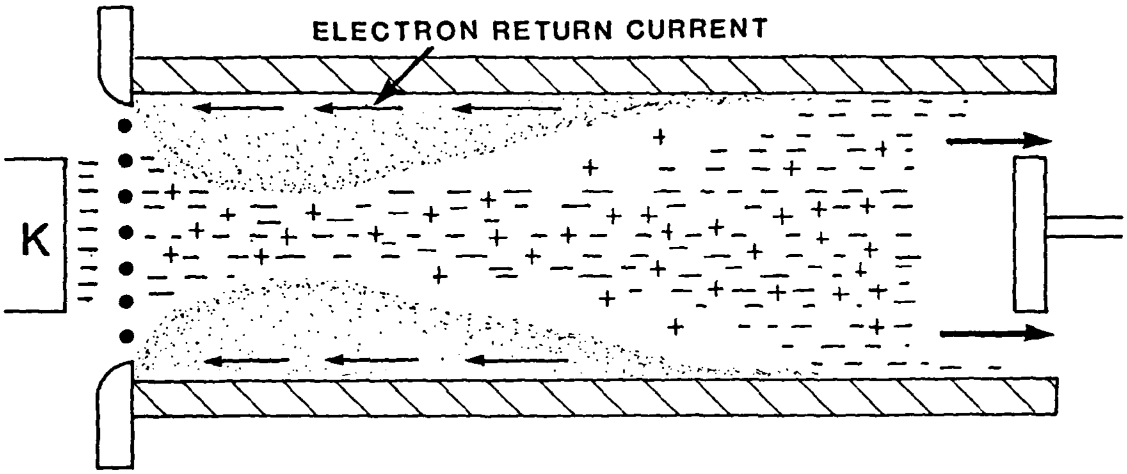


(a) BEAM REFLECTS, STRIKES GUIDE

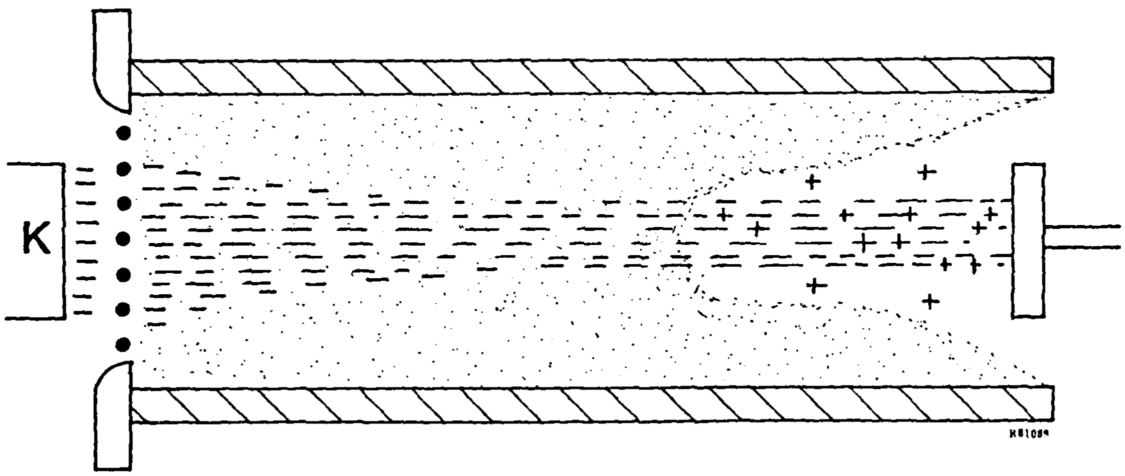


(b) PARTIAL NEUTRALIZATION, PROPAGATION BEGINS

FIGURE 4-1. ELECTRON BEAM PROPAGATION MODEL



(c) COLUMN WELL NEUTRALIZED, BEAM REFLECTED AT MOVING FRONT



(d) PLASMA FILLS GUIDE, AIDING PROPAGATION

FIGURE 4-1. ELECTRON BEAM PROPAGATION MODEL (Concluded)

The lack of correlation between the beam-front velocity and the maximum electron energy in the experiments at Spire may be explainable by a model in which the ions, whose "steady-state" velocity determines the speed of the electron beam front, are launched down the guide before the virtual cathode reaches its maximum potential. All experiments with dielectric guides show an initial delay of several nanoseconds when the beam arrival time-position curves are extrapolated back to the entrance of the guide. Presumably, this period represents the time to break down the surface of the guide, to inject ions into the potential well of the virtual cathode, and to initiate downstream propagation.

The time for a proton to accelerate from the wall to the center of the guide can be estimated by the quarter-period of a positive ion falling into a homogeneous cloud of negative space charge.[10]

$$t_{1/4} = \frac{\pi}{4} R \left(\frac{m_i}{2qV} \right)^{1/2} \qquad (4.1)$$

R and V are, respectively, the distance and potential difference between the wall and center of the cloud, and m_i and q are the mass and charge of the ion.

In the experiments at Spire, the potential represented by protons moving at a front velocity of 5×10^6 m/s is 130 kV, and with a guide radius of 1.9 cm, Eq. (4.1) gives a quarter-period of 3 ns. The observed time delay before propagation was 10 ns or less, compared to about 25 ns for the electron accelerator to reach its peak voltage. A similar calculation for the experiments on Gamble I, in which a front velocity of about 1.5×10^7 m/s was observed, gives a quarter-period time of only 1.5 ns. Thus, the velocity of the ions which determine the beam-front speed must depend on the detailed time history of the potential well while the ions are being liberated and accelerated from the walls of the guide. It has been shown theoretically that the instantaneous potential of the virtual cathode in front of a pulsed, space-charge-limited electron accelerator can be greater than the diode voltage.[25] This may account for the observations in other experiments in which the energy of a proton moving at the front velocity is somewhat greater than the peak voltage on the accelerator.[9]

The quasi-exponential loss of transported beam current with distance of propagation in the experiments at Spire is similar to measurements of the axial dependence of electron current from a Luce diode.[13] Very sharp axial current gradients are observed until near the end of the pulse. Additionally, Adler et al. at Cornell have reported that a coating of dielectric material on the metallic walls of the drift tube improves the electron beam transport downstream from the diode.

4.2 COLLECTIVE ION ACCELERATION

4.2.1 Experiments at Spire

Collectively accelerated ions were observed in earlier work at Spire with a lower energy, more slowly rising electron current injected into cylindrical dielectric guides.[2,3,4] Experiments at other laboratories at higher energy also showed considerable ion fluxes with energies up to 10 times that of the electron beam.[7,8]

In the recent series, the SPI-PULSE 600 electron accelerator was operated over a wide range of charging voltages and diode parameters in an attempt to observe collectively accelerated ions. We were, however, unable to detect ions in cylindrical or conical guides of several different diameters, lengths, and materials.

The diagnostics used to search for collectively accelerated ions were the same as used during our earlier experiments with beams from Spire's SPI-PULSE 6000 accelerator in which strong ion acceleration was observed. Ion current measurements were to be made in a Faraday cup placed behind collimating apertures and a transverse magnetic field to sweep away the electron beam. No accelerated positive ion current was observed above the noise level of the experiment, which corresponded to an ion current of less than 10 mA.

The ion current required to neutralize partially an electron beam is given by

$$I_i = f \frac{v_i}{v_e} I_e \tag{4.2}$$

where $f = n_i/n_e$ is the fractional space charge neutralization, v_i and v_e are respectively the ion and electron velocities, and I_e is the electron beam current. Assuming a 1 kA, 200 keV electron beam, protons with a velocity of 5×10^6 m/s (as observed for the beam front speed), and a neutralization fraction of 0.5, Eq. (4.2) predicts a current of 12 A of 130 keV protons.

In the earlier work at Spire, ion currents up to 0.6A were registered in the apertured Faraday cup. The Faraday cup intercepted less than 5 percent of the total ion current, so that more than 12A of ions were accelerated in the earlier experiments.

The principal differences between the original ion acceleration experiments at Spire and the recent work were in the characteristics of the electron accelerator. The SPI-PULSE 6000 is a 1.8-ohm charged dielectric transmission line with a stored energy of about 450 joules when charged to 300 kV. The electron current pulse from the diode rises almost linearly with time to a maximum at about 70 ns, while the voltage has already peaked at about 15 ns and decreases monotonically to nearly zero at 70 ns. The SPI-PULSE 600 accelerator is a 9-ohm charged line with a stored energy of 150 joules when charged to 400 kV. The current pulse is approximately constant after an initial rise in about 10 ns; the voltage reaches its peak in 20 to 25 ns. The pulse width of both voltage and current is about 40 ns (FWHM).

It appears presently that the lack of ion acceleration in the experiments with the SPI-PULSE 600 is due to the short duration of the voltage and current pulses. The experiments at Cornell University(13) and Lebedev Physical Institute(7) both indicate that the ions with energies several times greater than the electron beam energy are observed rather late in the pulse, even after the arrival of the electron beam front at the ion detector.(13) These results may indicate that the low-temperature plasma from the accelerator anode or guide walls must travel several centimeters downstream and be fairly homogeneous before the energetic ions are generated. In this case, the ion acceleration mechanism is probably a beam-plasma interaction rather than acceleration in a traveling or collapsing potential well.

As pointed out in Section 4.1, the time for a proton to be accelerated from the wall plasma into the center of the guide is of the order of 3 nanoseconds. This period must be increased by several times to allow for the time of plasma formation (a few nanoseconds) and randomization of the ion trajectories to form a high temperature, partially neutralized beam plasma.

It appears likely that the beam current and energy from the diode of the SPI-PULSE 600 have reached their peak and started to decay before a plasma has formed with enough density and longitudinal homogeneity to generate the instability which causes ion acceleration. Possible methods to speed up the processes of plasma formation and increase the longitudinal uniformity are discussed in Section 4.4.

4.2.2 Experiments at NRL

The experiments on Gamble I were designed to investigate ion acceleration in a range of electron currents considerably greater than the Alfven limit ($\nu/\gamma < 2.6$) and to determine if there is a dependence of ion energy on guide length. Our earlier work had indicated a positive correlation between electron current density, guide length, and ion energy.[3,4]

Analysis of the experimental results indicates that the detected collectively accelerated ions came principally from the anode foil of the field-emission diode. Shots in which metallic meshes were substituted for the aluminized Mylar anode showed very little neutron emission and activation of the copper foils. Shots with the aluminized Mylar anode foils, on the other hand, gave neutron counts as high as 10 times background and activation in copper foils 0.254 mm deep in the stack, indicating accelerated protons with energies greater than 11.6 MeV.

The principal effect of the Lucite guides was to enhance the electron current transmitted to the Faraday cup. A control shot with an aluminized Mylar anode and no dielectric guide showed as many accelerated ions as in identical shots in which the 30.5-cm long guide was present, although the transmitted electron current to the Faraday cup decreased by more than a factor of six. The Faraday cup was located in the same position as before removing the guide. The peak electron current transmitted through the 61-cm long guide was almost a large as through the 30.5-cm guide, although the coppper-foil activation decreased by a factor of about four. The electron current transmitted through the 91-cm long guide was less than 2% of the current injected from the diode, and the nuclear activation in the copper foils was about 3% of that observed with the 30.5 cm long guide.

All the results from Gamble I indicate that the accelerated ions came from the diode region, and, in particular, from the anode foil. Because there were no time-resolved measurements, the experiments did not show whether the ion acceleration occurred near the anode itself or downstream. The strong dependence on the cathode geometry and anode-cathode gap observed in the yield of accelerated ions suggests, however, that the diameter and current density of the electron beam are very important in the acceleration process. Of course, changes of the cathode diameter or anode-cathode gap influence more than one electron beam parameter, since the temporal behavior of the diode impedance depends on the diode geometry.

4.3 LUCE DIODE EXPERIMENTS

A recent series of experiments by Adler et al.[13] of Cornell University on Luce diodes shows strong similarities with our work on beam propagation and collective ion acceleration in dielectric guides. Measurements of the arrival time of the high-energy component of ions show clearly that the acceleration occurs only after the partially neutralized electron beam has propagated several tens of centimeters downstream from the diode. Measurements of ion yield with axial distance further show that the ion acceleration does not take place in the potential well in the anode region or in the moving well at the head of the propagating electron beam. Collective acceleration of ions appears to be accompanied by strong radio-frequency emissions.

Adler et al. argue that the ion acceleration is caused by a traveling wave and suggest the well-known two-stream instability as the acceleration mechanism. Further, measurements of the axial distribution of high-energy ion impingement on the wall of the drift tube indicate that the ions are not well confined radially and suggest that the confinement is related to the space charge neutralization in the propagating electron beam. Although a higher degree of charge neutralization produces better electron beam propagation, the weaker radial electric fields allow the accelerated ions to escape and reduce the total transmitted ion current. Similar, although somewhat less definitive, results were obtained by Bistritsky et al.[12] in Luce diode experiments in the USSR.

There are several similarities between the Luce diode experiments and Spire's and other measurements of ion acceleration in evacuated dielectric guides. The observations that the ion acceleration energy scales with the electron current density above a threshold value and with guide length for distances up to 30 cm can be interpreted as the result of an instability in the plasma. The threshold for growth of the two-stream instability is a function of electron current density; the dependence on guide length could be related to axial gradients in plasma and electron current density. Furthermore, dielectric guide experiments[8] at NRL showed that a considerable fraction of the accelerated ions were lost to the walls of the guide in a manner very similar to the measurements of Adler et al. It would appear that the energy and yield of collectively accelerated ions depend on a competition between the growth of the plasma instability, which is enhanced by the low temperature plasma, and ion losses when the neutralization of the electron beam is too high to provide effective electrostatic confinement of the energetic ions.

4.4 ION ACCELERATION IN MODIFIED GUIDES

4.4.1 Model

The experimental results of Bistritsky et al.[12] and Adler et al.[13] indicate that the acceleration of high energy ions from Luce diodes takes place in the downstream plasma, several centimeters from the diode structure. The acceleration is believed to occur in traveling space charge waves caused by a plasma instability of the two-stream type. If this model is correct, the growth of the instability should be strongly influenced by the density and homogeneity of the low-temperature plasma and of the relativistic electron beam.

Adler et al. argue, further, that a large fraction of the accelerated ions are lost radially because of the outward $v_z x B_\Theta$ force on the ions by the magnetic field of the propagating electron beam. Only those ions which are accelerated when there is sufficient electrostatic confinement by the negative space charge of the electron beam are observed at the end of the drift tube. The longitudinal distribution of nuclear activation in the drift tube of Adler's experiments would indicate that the average fractional neutralization of the electron beam by the plasma was about 95%.

The experiments of Pasour et al.[8] show a similar distribution of nuclear activation on the wall of a dielectric guide into which a relativistic electron beam was injected. These experiments and work at Spire indicating that the collectively accelerated ions were detected late in the electron beam pulse[3,4] would indicate that the same physical acceleration mechanisms are involved in both types of experiments.

4.4.2 Guide Modifications

The model of ion acceleration and containment summarized above suggests that more efficient ion acceleration could take place if the plasma and beam homogeneity in the drift tube or dielectric guide were improved. Furthermore, radial confinement of the high-energy ions should increase if the azimuthal magnetic field of the electron beam were reduced.

Modifications of the dielectric guide to achieve both of these ends is shown schematically in Figure 4-2. A cylindrical metallic insert would be placed in the center of the guide and electrically connected to the anode screen. An annular electron beam whose current, I_1, is much larger than the space charge limit would be injected between the dielectric and metallic cylinders. A part of the injected current would return to the anode of the accelerator through the center conductor.

The magnetic field from the central current will reduce the pinching of the electron beam in the drift region and the outward deflection of the ion current. At the unneutralized front of the electron beam, the electrons will strike the walls of the dielectric guide and the metallic cylinder and generate plasma. The plasma will partially neutralize the space charge of the beam and provide ions for collective acceleration. The reduced pinching of the electron beam should increase the radial and axial homogeneity of the electron current density in the drift region and increase the growth rates and spatial extent of the plasma instability responsible for collective ion acceleration.

The azimuthal magnetic field in the drift region is given approximately by the expression,

$$B_\theta(r) = \frac{\mu_o}{2\pi r}\left[I_2 - \frac{r^2 - a^2}{b^2 - a^2} I_1\right] \quad (b>r>a) \tag{4.3}$$

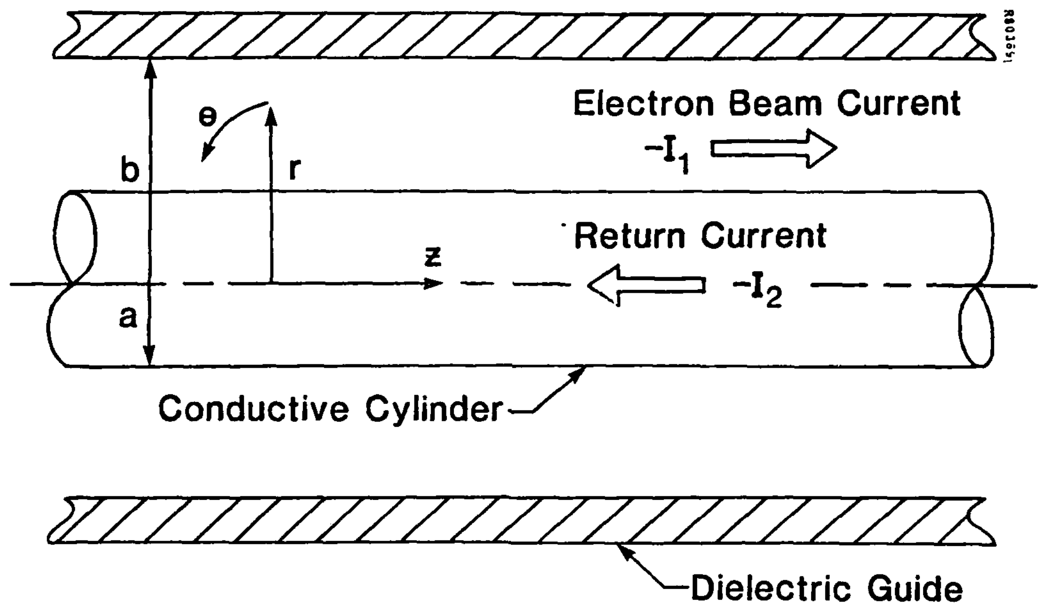


FIGURE 4-2. MODIFIED GUIDE CONFIGURATION

where I_2 is the current in the central conductor of radius a, r is the radial distance from the axis of symmetry, b is the inside radius of the dielectric cylinder, and ϵ_o is the permeability of free space. It is assumed that the electron current density is uniform in the volume between r = a and r = b. Rationalized m.k.s. units are used exclusively.

The direction and magnitude of the field depend on the value of the return current, I_2. When $I_2 = 0$, the field is in the negative Θ direction and causes pinching of the electron beam and divergence of a positive ion beam. When I_2 is equal (and in the opposite direction) to the electron beam current, the magnetic field is in the positive direction throughout the volume between the inner and outer cylinders.

The radial force on a particle with charge q and axial velocity v_z is given by,

$$F_r = \frac{qI_1(r^2-a^2)}{2\pi\varepsilon_o \beta_e c(b^2-a^2)r} \left[f-1 + \frac{\beta_e v_z}{c} \left(1-g \frac{b^2-a^2}{r^2-a^2} \right) \right] \qquad (4.4)$$

The axial speed of the electron beam is $\beta_e c$ and the fractional neutralization of the electron beam, $f = n_i/n_e$. The fraction of return current in the conductive central cylinder is $g = I_2/I_1$.

Equation (4.4) shows that there is a radial position at which the radial force disappears,

$$r_o = \left[a^2 + \frac{g(b^2-a^2)}{1 + \frac{c}{\beta_e v_z}(1-f)} \right]^{1/2} \qquad (4.5)$$

For relativistic electron beams which are nearly completely neutralized,

$$r_o \approx \left[a^2(1-g) + gb^2 \right]^{1/2} \quad \left(\beta_e \approx 1,\ f \approx 1 \right) \qquad (4.6)$$

For a typical guide configuration in which $a/b = 3/4$, the force-neutralization radius is halfway between the inner and outer cylinders when $g = 0.46$. It thus appears possible to accelerate ions in a region of small radial deflection when approximately half of the electron beam current returns on the central conductor. In the same volume, the radial force on the beam electrons is small at the same position because of the weak dependence of r_o on the axial beam velocity.

A time-varying beam and return current will not change the above conclusions because the electric field induced by a varying azimuthal magnetic field is only in the axial direction.

A problem to be addressed is the control of the fraction of electron beam current which returns through the central conductor. We believe that this current can be influenced by changing the configuration of the central cylinder. For example, thin metallic rods or wires arranged in a cylindrical pattern would intercept a smaller fraction of the electron beam than a solid cylinder. Other techniques, such as constructing the central cylinder of a dielectric with a thin coating of metallic or semiconducting material, may also be feasible. A dielectric cylinder may, in fact, have enough radiation-induced surface conductivity to provide the return current path. A transparent mesh placed at the end of the guide and electrically connected to the central cylinder can also be used to shunt part of the beam current after the beam front reaches the end of the center conductor.

SECTION 5
SUMMARY AND RECOMMENDATIONS

5.1 SUMMARY

5.1.1 Electron Beam Propagation

Experiments at Spire using dielectric guides of several configurations, including cylinders of several diameters and materials, cones, and shortened cylindrical guides indicate that the beam-front velocity is independent of the materials, dimensions, total injected current, current density, and to a limited extent, the electron beam energy. We conclude that the beam-front speed is determined by processes occurring in the inlet volume of the guide, and probably in the region of virtual cathode formation just downstream from the accelerator anode.

Neutralizing ions formed by breakdown of the inner walls of the dielectric guide are drawn into the virtual cathode region on a time scale of a few nanoseconds (less than 10), and the beam begins to propagate at a constant velocity which is not influenced by the walls of the dielectric guide. A sharp onset of Faraday cup current is observed even in the region well downstream of the exit end of a shortened cylindrical guide, representing a beam-front region moving at constant speed.

The propagated electron current, on the other hand, depends strongly on the presence, and, to some extent, the diameter and material, of a dielectric guide. The electron beam current is lost principally at the beam front, since the front moves at a speed considerably less than that of the accelerated electrons (0.01c to 0.1c vs. approximately c). There was also an approximately exponential loss of the peak transmitted current with guide length in the experiments with the SPI-PULSE 600 at Spire. The latter losses may be dependent on the pulse duration from the accelerator, since other experiments using accelerators with lower impedance and more slowly rising pulses of electrons indicated that a large fraction, up to 80%, of the beam current was propagated after the arrival of the sharp front at a collector. The shorter pulses from the SPI-PULSE 600 accelerator may not allow enough time for the formation of a well-neutralized beam plasma.

5.1.2 Collective Ion Acceleration

In contrast with the earlier series of experiments at Spire using the 1.5 ohm SPI-PULSE 6000 electron accelerator, no collectively accelerated ions were observed in experiments using the 9-ohm SPI-PULSE 600 accelerator. The major differences between these experiments were the shape and duration of the current and voltage pulses from the accelerators. The SPI-PULSE 6000 delivers a fast-rising voltage pulse, followed by a linearly increasing current which peaks approximately 100 ns after the voltage. The SPI-PULSE 600 has a much faster current risetime, with approximately constant current output over 30 ns of its 40 ns pulse duration. The fast risetime, constant current output and short pulse duration of the accelerator may not excite a high enough level of plasma waves or turbulence to produce effective collective ion acceleration. A minimum time and plasma density may be required for the establishment of accelerating conditions.

The experiments on Gamble I at NRL showed ion acceleration more than 14 times the electron energy (11.6 MeV vs. 800 keV). In these experiments, appreciable numbers of energetic ions were observed only when an aluminized Mylar or aluminum foil was used as the anode of the electron accelerator diode. Although considerable electron currents were propagated down the guide when steel mesh was substituted for the anode foil, very little nuclear activation was observed in copper targets with an activation threshold of 4.2 MeV.

A control shot with the dielectric guide removed showed as much activation in the copper targets as with the guide present, although a much smaller fraction of the electron current was propagated than with the guide in place. These results show that the collectively accelerated ions observed in experiments with dielectric guides originate in the anode foil or from the inlet end of the guide very near the anode plane. The plasma instability mechanism responsible for high acceleration energies apparently operates only a short distance downstream from the anode, and can only occur under optimized conditions of plasma density and longitudinal profile, current density, and perhaps other parameters.

The results of these experiments give strong evidence that collective ion acceleration in evacuated dielectric guides is the same, or a similar, process to ion acceleration in "Luce" diodes. An instability, probably of the "two-stream" type, creates plasma turbulence with a high level of electric field fluctuations. The turbulent electric field accelerates a small component of the plasma ions to the observed high energies. The dielectric guide downstream of the anode region may operate in an analogous way to the dielectric "lenses", which in some Luce diode experiments are found to enhance the yield of accelerated ions and propagated beam current.

If, indeed, the acceleration of ions to high energies in dielectric guides and Luce diodes is a plasma dynamic process in the downstream volume, then it may be possible to influence the acceleration mechanisms to increase the ion energy and yield. There may be techniques to increase the plasma volume in which the ion acceleration takes place, increase the coherence of the unstable plasma waves, or provide better radial confinement of the accelerated ions.

In Section 4.4.2 we have suggested a possible method of influencing the acceleration mechanisms. A coaxial guide geometry should provide a longer, more homogeneous plasma in the beam propagation volume than in a simple cylindrical geometry. If, in addition, the inner cylinder provides a return current path for a significant fraction of the electron beam, the magnetic field in the guide could be reduced to the point of aiding electron and ion beam propagation.

5.2 RECOMMENDATIONS

We recommend that further theoretical and experimental investigations be conducted to establish clearly the connection in collective ion acceleration between dielectric guides and Luce diodes. This study would lead to a much more general understanding of collective acceleration processes in which the positive ions are injected into a relativistic electron beam in the anode region.

Additionally, we recommend that a parallel and complementary effort be made to control the acceleration process in dielectric guides by modifying the physical conditions in the plasma volume a few centimeters downstream from the anode of the electron accelerator. A possible technique, discussed above, is to reduce the plasma density gradients and self-generated magnetic fields in the propagating electron beam.

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